

**A Framework for Preliminary Design of Aircraft Structures Based on
Process Information**

Final Report - Part 1

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by

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Summary

This report discusses the general framework and development of a computational tool for preliminary design of aircraft structures based on process information. The described methodology is suitable for multidisciplinary design optimization (MDO) activities associated with integrated product and process development (IPPD).

The framework consists of three parts: (1) product and process definitions; (2) engineering synthesis, and (3) optimization. The product and process definitions are part of input information provided by the design team. The backbone of the system is its ability to analyze a given structural design for performance as well as manufacturability and cost assessment. The system uses a database on material systems and manufacturing processes. Based on the identified set of design variables and an objective function, the system is capable of performing optimization subject to manufacturability, cost, and performance constraints.

The accuracy of the manufacturability measures and cost models discussed here depend largely on the available data on specific methods of manufacture and assembly and associated labor requirements. As such, our focus in this research has been on the methodology itself and not so much on its accurate implementation in an industrial setting.

A three-tier approach is presented for an IPPD-MDO based design of aircraft structures. The variable-complexity cost estimation methodology and an approach for integrating manufacturing cost assessment into design process are also discussed.

This report is presented in two parts. In the first part, the design methodology is presented, and the computational design tool is described. In the second part, a prototype model of the preliminary design Tool for Aircraft Structures based on Process Information (TASPI) is described. Part two also contains an example problem that applies the methodology described here for evaluation of six different design concepts for a wing spar.

1. Addressing Manufacturability and Cost Assessment in Airframe Design

The influence of product design on its manufacturability is well documented in the literature. Methodologies such as integrated product and process development (IPPD) have become popular tools for addressing product life-cycle issues early in the design process before the product goes into production. Although the philosophy behind IPPD is well understood, its efficient application to many products including flight vehicle structures is still evolving through continued research. A major challenge is the development and implementation of methodologies that efficiently address manufacturability and cost assessment early in the design process.

Figure 1 describes two different approaches that could be used for structural (product) design and development. It uses a wing structure as an example. In the first approach identified by letter S, the preliminary design of the structure is first optimized for a measure of performance based on structural constraints. In this case, manufacturability and cost assessment are considered as a post-optimization activity, and as such often lead to subsequent structural design modifications. Upon several iterations between the structural design and manufacturing teams, a manufacturable design may emerge which may still be far from optimum in terms of manufacturability and cost as well as performance.

The alternative approach identified by letter I in Fig. 1, represents an integrated scheme. Here, the manufacturing processes to be used for each part are identified at the beginning of the structural design. Based on the structural definition and process information, cost estimating rules can be established. Structural design, manufacturing process, and cost attributes are

defined and linked in a manner that enables the optimization of the whole system based on performance as well as manufacturability and cost requirements. Alternative design concepts and manufacturing processes could be examined in a trade-off study at the preliminary design level prior to the initiation of the detailed design. This approach is consistent with the goals of IPPD, and improves the design efficiency and facilitates subsequent activities in prototype development, testing, and production.

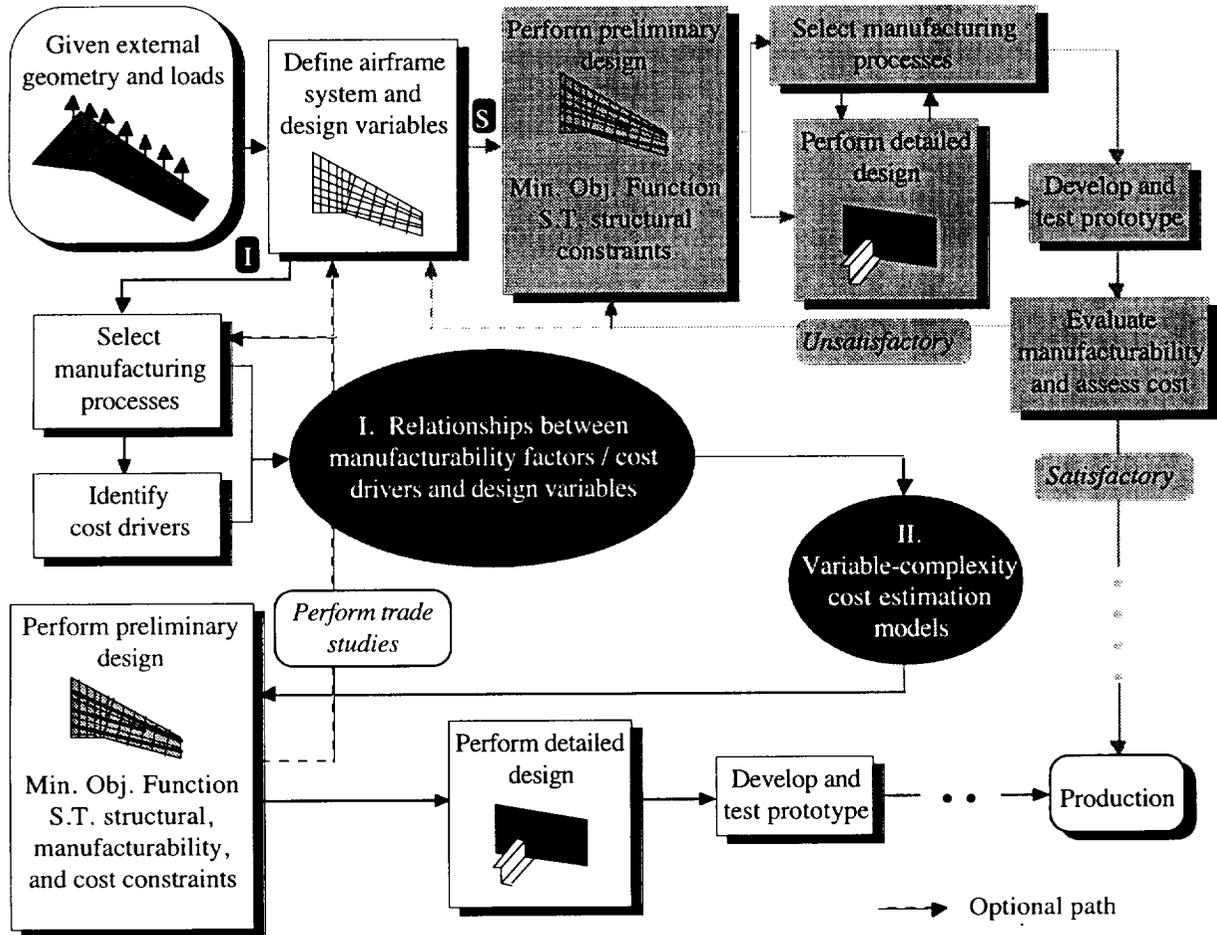


Figure 1. Two alternate approaches in structural design

The integrated approach as described here represents product design optimization with manufacturability and cost constraints. Ideally, product design optimization would need to be coupled with process design optimization in order to find the optimal product-process combination. Nonetheless, the integrated approach as described here is deemed more efficient than the alternative sequential approach as product and process interactions are accounted for in the product optimization analysis.

1.1 Airframe Manufacturability Factors and Cost Drivers:

To implement the integrated method it is necessary to formulate the relationships between designer-controlled variables and process-dependent parameters. These relationships are established through the identification and modeling of the manufacturability factors listed in Table 1. The manufacturability factors for a generic product were first introduced by Shankar

and Jansson¹, and were then expanded and applied to airframe structures by Rais-Rohani.² For complete description of these factors refer to ref.2.

Table 1. Generalization of manufacturability factors

Compatibility	Complexity	Quality	Efficiency	Coupling
Material-Material	Intricacy	Design Flaws	Material Usage	Material
Material-Process	Tolerances	Robustness	Part Count	Process
Configuration-Process	Symmetry		Operations	Configuration
Material-Configuration	Uniformity		Standardization	
Availability	Accessibility		Variety	
	Orientation			
	Handling			
	Special Requirements			

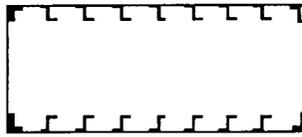
Cost drivers are defined as factors with significant influence on manufacturing cost. Cost drivers have direct impact on cost elements which can be categorized as: equipment, labor, material, and energy. Our main focus is on designer-influenced cost factors affecting the total manufacturing cost which includes both recurring and non-recurring costs.

To highlight the effects of design decisions on manufacturability factors, let us consider three different wing box design concepts as shown in Fig. 2. In the first concept (Fig. 2-a) the wing box is of skin-stringer type with the upper and lower skins stiffened with a number of Z stringers. In the second concept (Fig. 2-b) the wing box utilizes a sandwich skin thereby reducing the requirement for a large number of stringers. In the third concept (Fig. 2-c) the wing box is of a multi-spar configuration with the spar caps supporting the skins without the use of any stringers.

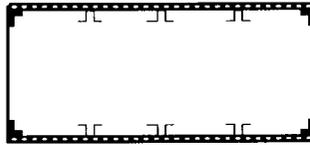
These three design concepts are assumed to be equally capable of supporting the applied loads; however, each does it in a different way and with different degrees of efficiency and complexity. Furthermore, the requirements regarding structural integrity and reliability are also assumed to be adequately satisfied by all three design concepts.

Comparing wing box design concepts in Figs. 2.a and 2.b, we observe that while the number of stringers in (b) is less than that in (a), the skin design in (b) is more intricate and also requires more parts in its construction than that in (a). Design concept (c) on the other hand has no stringers, but has two additional spars compared with the previous two. In design concepts (c) and (b) additional complexity has accompanied the reduction in number or removal of stringers.

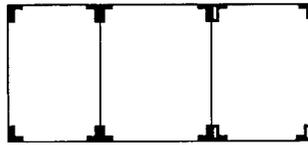
The optimum wing box design in this case would be the one with the best balance between performance, complexity (measured for example in terms of *intricacy*), and efficiency (measured for example in terms of *part count*).



a. Thin skin, heavily stiffened configuration



b. Thick skin, lightly stiffened configuration



c. Multi-spar configuration

Figure 2. Design complexity and efficiency comparisons for three different wing box design concepts

1.2 Manufacturability Measures and Indices:

To quantify the manufacturability factors listed in Table 1 two different metrics are used: manufacturability measure; and manufacturability index.¹ The manufacturability measure is a metric that is obtained primarily from an analysis of the manufacturing process, whereas the manufacturability index is a metric that is obtained primarily from an analysis of the product, in this case the aircraft structure. To determine manufacturability measures, the process plan is used to identify the tasks which affect the efficiency of the process. For example, the numbers of labor intensive operations, adjustments, tool changes, etc. can be used as measures that allow the designer to identify the design features which make manufacturing difficult or costly. The manufacturability indices are directly linked to the design variables and, as such, can be controlled by the designer. For example, a manufacturability index can be calculated based on the geometrical shape of the structural part.

In order to address manufacturing requirements at the preliminary design level, it is necessary to establish relationships between the manufacturability factors and the designer-controlled parameters. For example, the structural manufacturability index associated with a complexity factor can be expressed in a generic form

$$CI = \sum_{i=1}^N C_i \quad (1)$$

where C_i is a complexity index (e.g., intricacy index) for the i^{th} part and N is the total number of parts in the assembly. For the case of a wing box, Eq. (1) can be expanded as

$$CI = \sum_{sk=1}^{N_{sk}} C_{sk} + \sum_{st=1}^{N_{st}} C_{st} + \sum_{sp=1}^{N_{sp}} C_{sp} + \sum_{r=1}^{N_r} C_r \quad (2)$$

where C_{sk} , C_{st} , C_{sp} , and C_r are complexity indices for skin panels, stringers, spars, and ribs, respectively. N_{sk} , N_{st} , N_{sp} , and N_r denote the quantity in respective groups. If the complexity factor for each group of parts is constant, then Eq. (2) reduces to

$$CI = N_{sk} C_{sk} + N_{st} C_{st} + N_{sp} C_{sp} + N_r C_r \quad (3)$$

If the skins, spars, and ribs have to be individually assembled prior to final wing box assembly, then the assembly complexity index could be expressed as

$$ACI = AC_{sk} + AC_{sp} + AC_r + AC_a \quad (4)$$

Where AC_a denotes the complexity index for wing box assembly. The overall system complexity index, SCI is then expressed as

$$SCI = CI + ACI \quad (5)$$

The complexity and efficiency of each wing design could then be judged based on the values of N and SCI .

Let us consider intricacy, as an example for complexity factor in Eq. (1). Intricacy characterizes the amount of detail in a structure, and we measure it in terms of structural features. The main features of a wing skin as shown in Fig. 3 consist of: material composition; spanwise and chord wise variations in thickness; surface contour, and the number, size, and shape of cutouts. If the skin is made of fibrous composites, then ply pattern is also included in material composition. Furthermore, if the skin is an assemblage of multiple panels, then the geometric shapes and sizes of the panels would also be considered for calculating the assembly complexity index in Eq. (4).

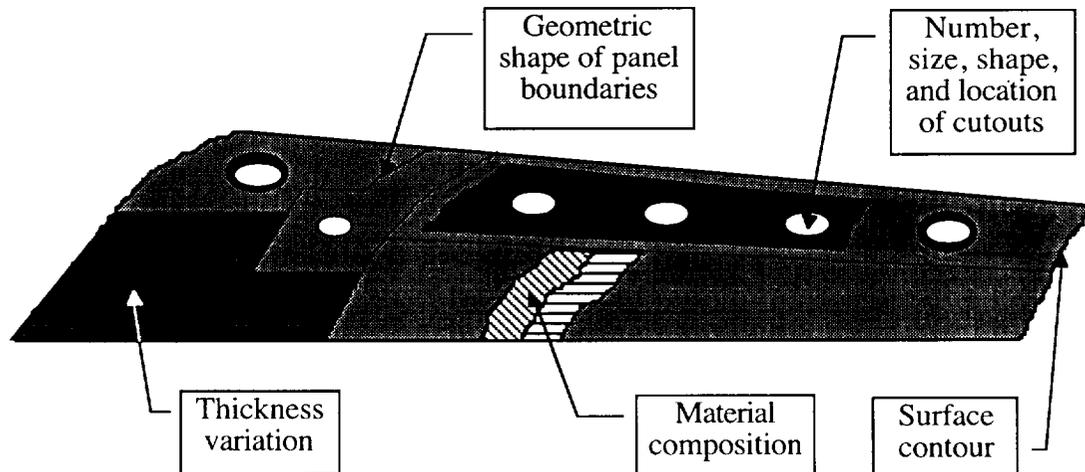


Figure 3. Features contributing to structural intricacy

Since these features are defined as or controlled by design variables, then a direct or an indirect relationship between design variable vector X and intricacy indices C_i can be established. The

limits associated with each feature are governed by the selected manufacturing process. For example, if the skin is to be machined from an aluminum plate, then the limits on thickness variation or cutout shape would be governed by the capabilities of the equipment used. Therefore, the allowables on intricacy, used in the formulation of manufacturability constraints, would vary from one manufacturing process to another. Consequently, a feature that would be very inexpensive to achieve with one process might be very costly or even impossible to obtain with another. Hence, the impact of intricacy on design could be amplified or reduced depending on the choice of manufacturing process.

For discussion of other manufacturability factors refer to ref. 2.

1.3 Formulation of Manufacturability/Cost Constraints:

Product and process attributes are used to formulate manufacturability constraints for product optimization. Figure 4 provides a graphical representation of the steps taken to formulate these constraints. First, product definition, including material and configuration information, is used to set up the desired design variable vector. Product definition alone can be used to evaluate some of the manufacturability factors and to obtain their corresponding indices. For example, the compatibility of selected materials as well as the compatibility of materials and configuration can be evaluated at this point. Furthermore, other factors such as intricacy, uniformity, part count, and variety can be evaluated based on product definition alone.

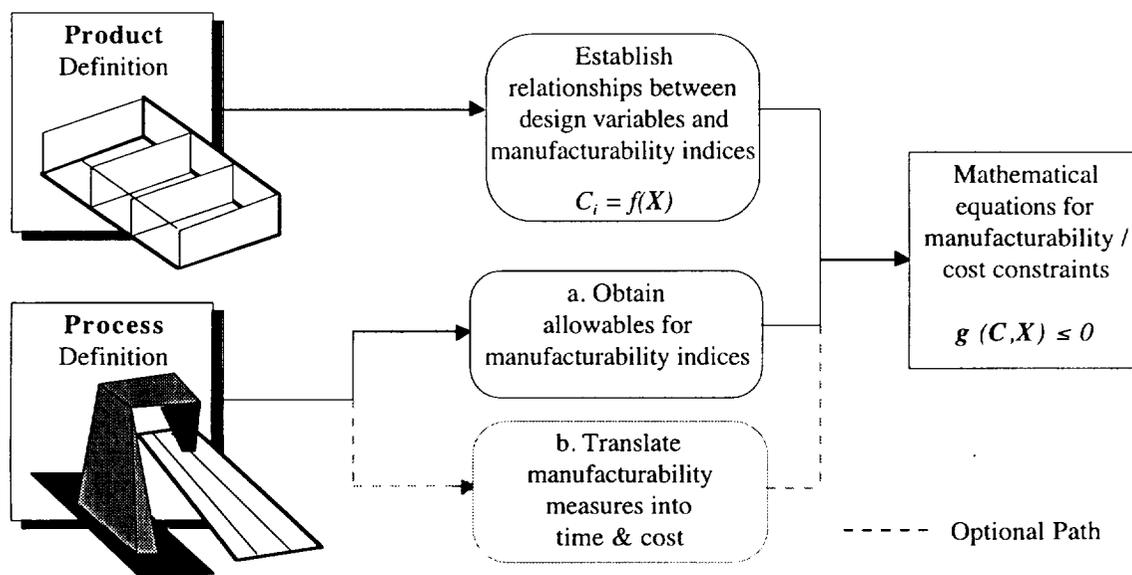


Figure 4. Procedure for the formulation of manufacturability/cost constraints

On the other hand, process definition is used to obtain information about the selected set of manufacturing processes. If the process information is limited to the allowable values, then manufacturability constraints can be formulated based on the actual and allowable values of manufacturability indices and measures. However, if more detailed information about the manufacturing process is available, from a simulation program for example, then it would be possible to obtain time and cost associated with the manufacture of the specified product, and that information could then be used for the formulation of cost constraints. This is treated as an optional path shown by dashed lines in Fig. 4.

1.4 Manufacturing Cost Estimation:

In airframe design both qualitative and quantitative measures of manufacturability and cost could be used. Cost drivers, for example, can be viewed as qualitative measures of cost which if properly controlled in the design process, could lead to a reduction in manufacturing cost. Quantitative measures such as machine time or energy consumption could be used to establish algebraic cost models. The cost estimation models are generally classified into two categories: (1) Parametric Cost Models (PCM); and (2) Manufacturing Process Cost Models (MPCM).

Parametric cost models are commonly expressed in terms of manufacturing complexity and cost estimating relations (CER). Although weight-based CERs are commonly used for cost estimation, experience shows that they do not accurately represent the actual manufacturing cost. Accurate determination of manufacturing complexity is the most difficult component of PCMs as it must include product- and process-specific parameters that can influence it.

The manufacturing process cost models require a thorough understanding of the manufacturing process involved in the production. They are constructed according to detailed estimation of the main cost categories of manufacturing such as material use, fabrication, assembly, and support labor hours. The manufacturing process cost models are formulated in such a way as to capture the costs associated with a given group of materials and the processes used in the fabrication and assembly of corresponding structures. When estimating the full production cost as opposed to the prototype cost, the recurring and nonrecurring portions of the manufacturing cost are identified and accounted for separately. These models tend to be more accurate than PCMs, but require more detailed information up front. Rais-Rohani and Dean³ give a description of some of the existing proprietary and academic codes used for cost estimation of aircraft structures.

The approach being explored in this research is that of variable-complexity cost estimation (VCCE). The term “variable complexity” refers to the complexity of cost equation and its degree of accuracy. This approach falls under the category of MPCMs described above. Fidelity of VCCE models depend on the extent of information available at each stage of the design process. For example, at the conceptual design phase when structural sizing information is not well defined, a model based on historical data on comparable structures could be used for an initial cost estimation. If a built-up structure of simple metallic parts is being designed, then it would be possible to estimate manufacturing cost primarily based on the assembly effort which is a function of part count and measure of individual part complexity. At this point comparison could be made with an alternative design which relies on machining process to generate the structure with far less part count. In this case machining as opposed to assembly cost would be treated as the major cost driver and based on that information a cost comparison could be made.

In the above cited examples, a low-fidelity cost estimation model could be used based on assembly and machining costs alone. This estimate simply represents the degree of effort involved in the manufacture of each structure, and is not meant to produce precise cost figures. It is conceivable that the cost estimates for two or more alternate designs at the conceptual level may not be very different. In that case, we must rely on other criteria to make a selection from among the alternate design concepts.

The fidelity of cost estimates improves in the preliminary design phase as the structural design and corresponding manufacturing process plan become better defined. At this point, structural part geometry, material system, and primary manufacturing processes must be specified. This specification leads to identification of product and process parameters that are then linked through the formulation of manufacturability factors.² The quantitative measures associated with these manufacturability factors are then used to estimate manufacturing cost.

Both deterministic and probabilistic approaches to cost estimation could be used. In the deterministic approach, cost estimating relations that link product and process parameters are used for the calculations of direct and indirect costs. MC/DG⁴ has been our main source of data for estimating direct labor and indirect costs based on the specified part features, material system, and manufacturing processes. In this case no uncertainty is assumed in the model or corresponding parameters. Therefore, the estimates obtained from this deterministic procedure are not robust as any slight parameter variation could affect the cost.

The probabilistic procedure has not been thoroughly investigated in this research. However, in such a procedure the manufacturing cost would be treated as a random variable that is a function of other random variables associated with the product or the manufacturing process. In this approach the investigation would be centered on determining the mean values of the random design variables such that the probability of manufacturing cost exceeding a certain value is below a set limit. In this procedure it is necessary to model all random variables including the design variables by suitable probability distribution functions. For example, if we assume each random variable has a normal distribution, then its mean value would be changed in the optimization process while maintaining its distribution function and coefficient of variation fixed. The cost estimates obtained through this procedure are supposed to be less susceptible to error as a result of minor changes in product or process parameters.

The purpose of VCCE, in general, is not to estimate the “true” cost in dollars as much as to obtain a realistic cost *measure* that would be useful to the designer for trade-off and optimization studies especially at the conceptual and preliminary design levels. Variable-complexity cost estimates improve in accuracy with design progression in the three-tier synthesis described next. As with other models, it would be possible to improve the accuracy of these cost measures by calibrating them using industry data for specific manufacturing process including labor skill, tooling requirements, and operation sequence.

2. A Strategy for IPPD-MDO Based Structural Design

To integrate manufacturability requirements and cost assessment with structural design in an IPPD-MDO framework, a three-tier strategy is proposed. The three tiers consist of pre-MDO synthesis, MDO analysis, and post-MDO validation as shown in Fig. 5.

In the first tier, a pre-MDO synthesis of the structural design is performed. The designer provides the input information by first identifying the structural system (e.g., wing box) in terms of its general attributes, part definitions, and design variables. In addition, the designer specifies the type and form of the material system (e.g., 7075-extrusion) and up to three major processes used in the manufacture of each structural part. For example, machining, solution heat treatment, and age creep forming could be identified as the three main processes for an aluminum wing skin. The designer also specifies the method of assembly for each part (if applicable) as well as that for the whole system. The method of assembly could be identified as: (1) fully manual; (2) fully automated; or (3) $a\%$ manual and $(100 - a)\%$ automated.

Based on the information given as input, the design tool will examine the manufacturability factors (see Table 1), identify the cost drivers and make an initial cost estimation based on the principles of VCCE described earlier. The output of pre-MDO synthesis includes: true material properties; some of the manufacturability measures; limitations on surface finish, maximum allowable nonuniformity in each part, as well as upper and lower dimensional bounds and permissible tolerances—all consistent with the processes selected. An initial manufacturing cost estimate is also provided as output. The manufacturability measures given as output in tier one could be used to accept or reject a design concept before proceeding to formal optimization in tier two. An example of tier one applied to a wing box structure is shown in Fig. 6.

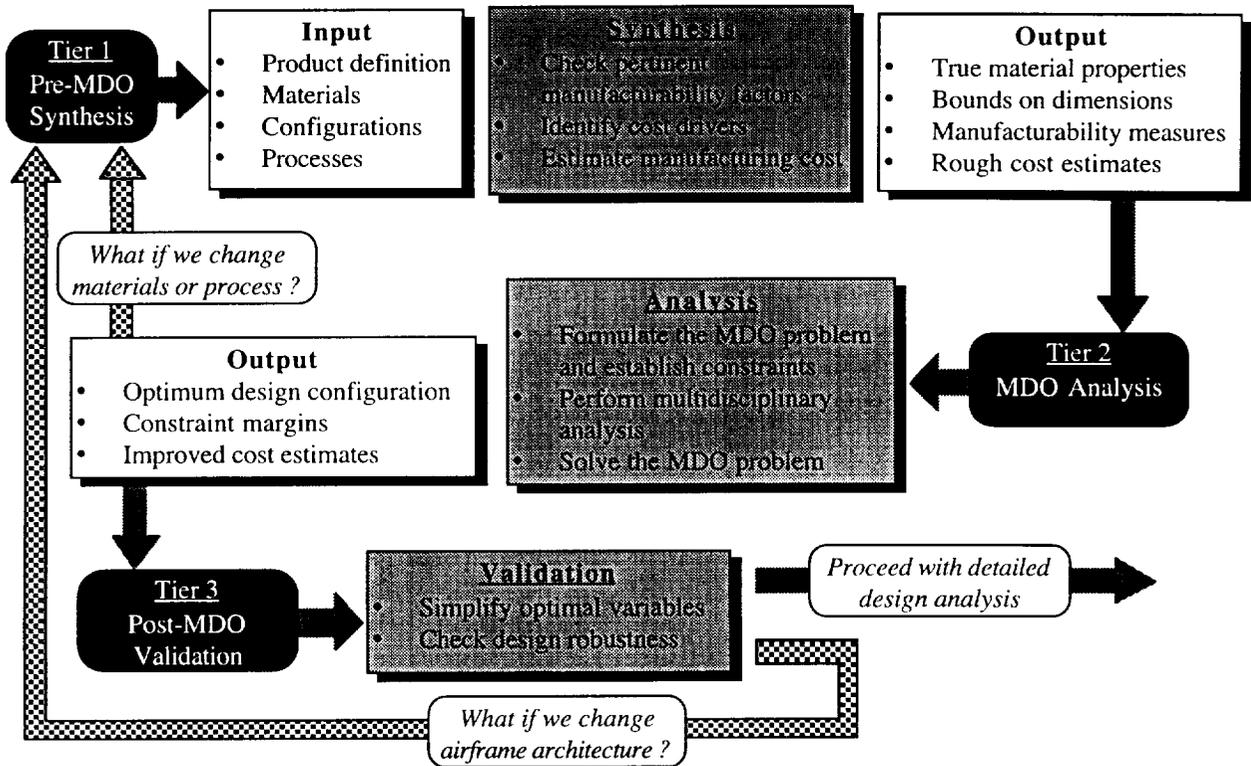


Figure 5. A 3-tier approach for IPPD-MDO based structural design

A single- or multi-level optimization procedure would be used for the solution to the MDO problem in tier two. The optimization analysis minimizes the objective function (e.g., structural weight) subject to a multidisciplinary set of design constraints on performance, manufacturability, and cost. Information related to complexity and other manufacturability factors are processed for the formulation of constraints on manufacturability factors and cost drivers (MF/CD) as shown in Fig. 4. The upper and lower bounds on sizing variables would be governed by the selected manufacturing processes. With relationships between the design variables and process parameters known, an optimal solution is sought. Once we obtain the optimal structural dimensions, we can improve on the manufacturing cost estimates found at the pre-MDO synthesis.

Once the optimization analysis is complete, two options can be pursued as illustrated in Fig. 5. One option is to return to the pre-MDO synthesis and select a different material or manufacturing process and repeat the analysis and optimization procedure. The resulting trade-off investigation can be used to find the best combination of material, process, and design configuration for the structural system being designed. The second option is to proceed to the post-MDO validation in tier three for fine-tuning of the design prior to detailed design, prototype development, and possibly production.

Design validation is carried out by checking design sensitivity to minor changes in the material properties or other parameters. This procedure checks the design robustness, and allows the designer to make minor adjustments to the design variables to improve the system's manufacturability and to reduce its manufacturing cost.

The strategy described above lends itself to a knowledge-based object-oriented computer software that would enable the designer to perform trade-off, sensitivity, and optimization

studies of airframe structures based on performance as well as manufacturability and cost requirements. The designer can use this software as a design guide and evaluation tool to examine different combinations of structural architecture, material system, and manufacturing process to obtain a design that meets the performance demands at an affordable cost.

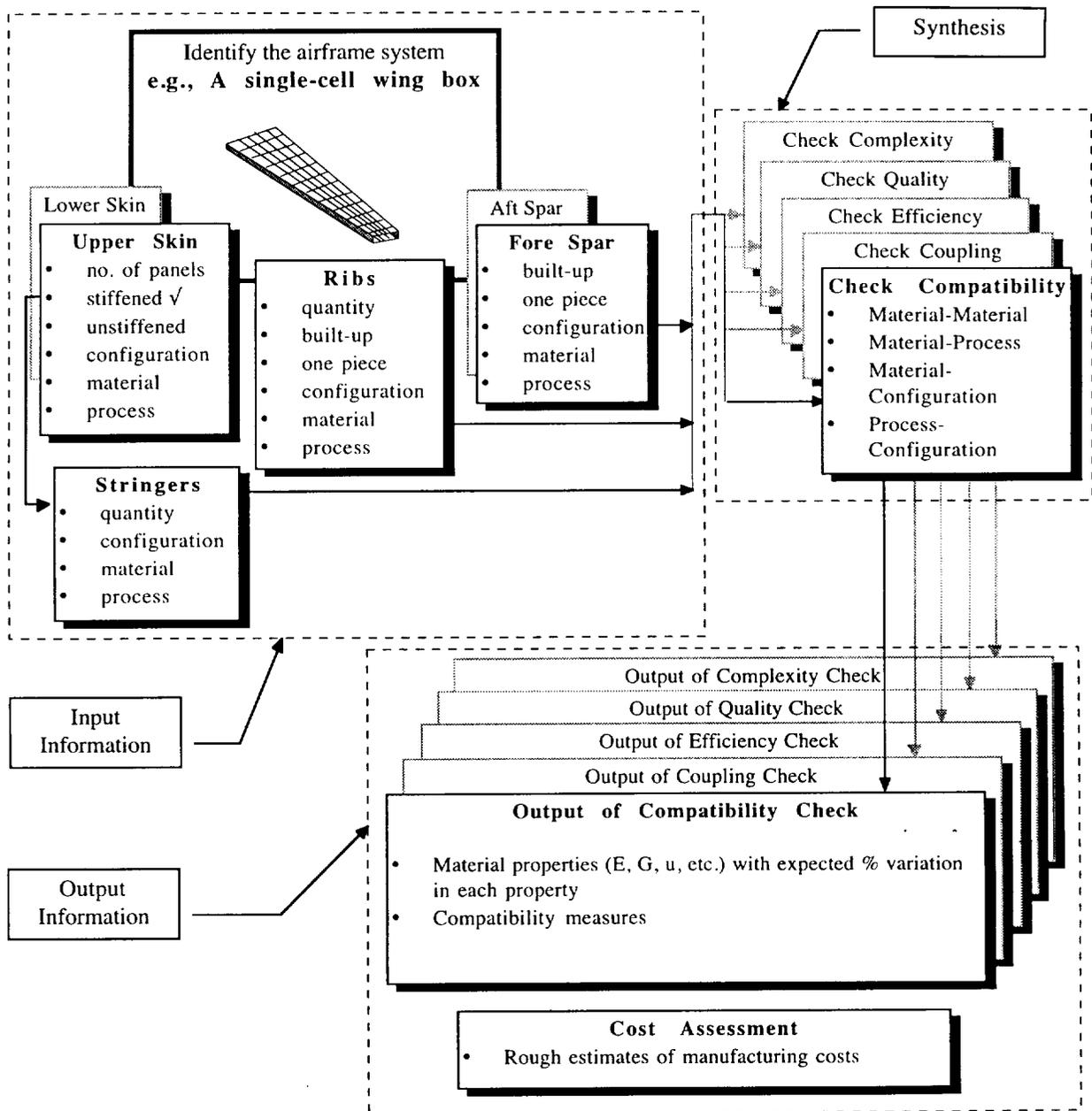


Figure 6. Pre-MDO synthesis: organizational diagram with compatibility check highlighted

3. Preliminary Design Tool for Aircraft Structures Based on Process Information

The procedure described earlier is being developed into a software called preliminary design Tool for Aircraft Structures based on Process Information (TASPI). In this section additional details about TASPI are provided. In particular, we will examine the input information and the options available for the design of a wing box structure.

TASPI could be used in either analysis or optimization mode. In the analysis mode, TASPI evaluates a given design and provides information on its structural response, manufacturability, and manufacturing cost. In the optimization mode, TASPI optimizes the structural design for a selected set of materials and manufacturing processes.

To use TASPI the user begins the design analysis/optimization process by providing detailed information describing the structural system. The user input is divided into four categories as shown in Fig. 7. Item 1, treated as an optional input, asks for information about the aircraft for which the structural system is being designed. This feature is included primarily for an initial cost estimation based on historical data in accordance with the VCCE methodology. Items 2 through 4 focus on the structural system itself. In item 2 the user is asked to define the system. For example, is the system being evaluated a single-cell wing, or a two-cell vertical tail. Next, the user is asked to provide information about the features of the system as well as its anatomy. User has to supply information about the general configuration, material, and major processes to be used in the manufacture of each part. An example of the input information for a single-cell wing box structural system is given in Table 2.

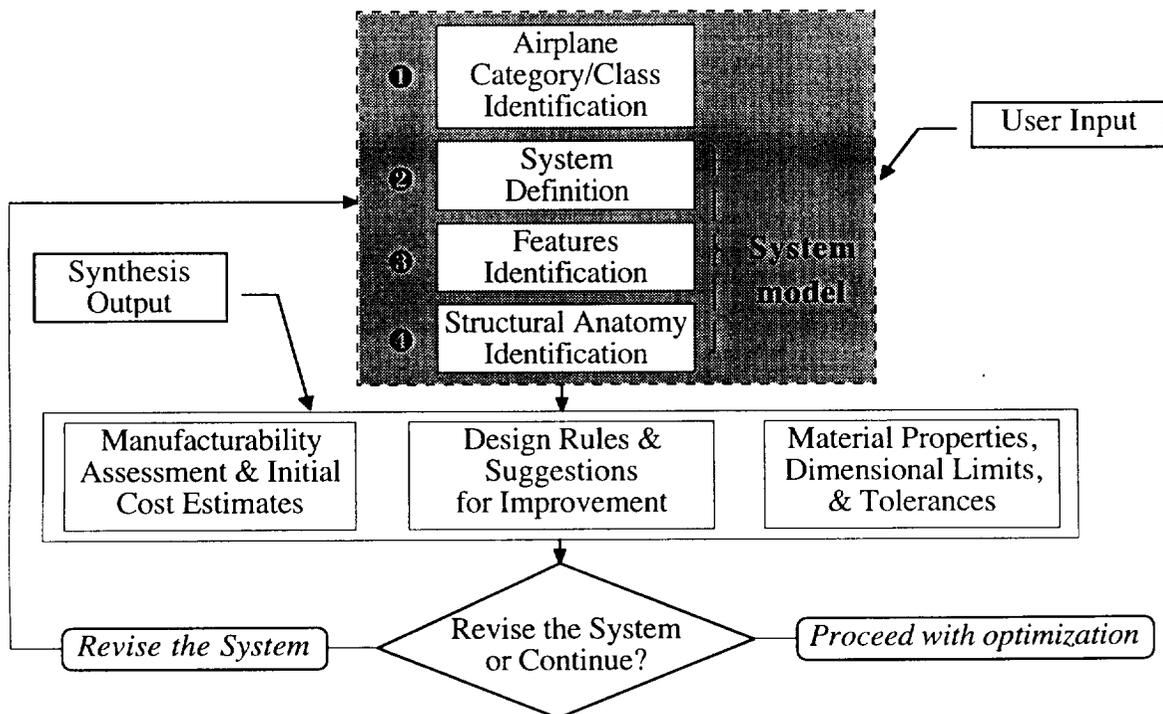


Figure. 7 Design definition and evaluation (Pre-MDO synthesis)

Based on the data submitted, TASPI will provide information on:

- a. manufacturability ratings
- b. cost estimate for each part,
- c. design rules and suggestions for design improvement,
- d. material properties for each part,
- e. dimensional limits and associated tolerances for each part,
- f. expected surface roughness for each part.

If the results of this pre-MDO synthesis are unsatisfactory, the user can return to a particular field and change the input data and reevaluate the system. At the user's discretion the program would store the evaluation output in a file for future reference.

The tool encourages the decisions at the design level to be made as much as possible in accordance with the manufacturing requirements. The designer will provide input either according to his knowledge of how each part will be manufactured or in collaboration with a manufacturing engineer member of the integrated product team (IPT).

The pre-MDO synthesis has to be performed initially before the design can be optimized. This is because many of the manufacturing-based constraints are formulated according to the limits obtained from the pre-MDO synthesis. With these limits as well as the true material properties known, a formal optimization can be performed as described in Fig. 8.

In the optimization mode, TASPI optimizes the design for a specified objective function (e.g., structural weight) based on a selected set of design constraints. Design constraints are imposed to satisfy structural response, margins of safety, and manufacturability/cost requirements. Sizing parameters comprise the majority of design variables that are altered in finding an optimum design. The general purpose optimization program DOT⁵ is used for optimization analysis. This program includes the following three optimization methods: method of modified feasible directions; sequential linear programming; and sequential nonlinear programming. Any one of these methods can be specified by the user through the input file.

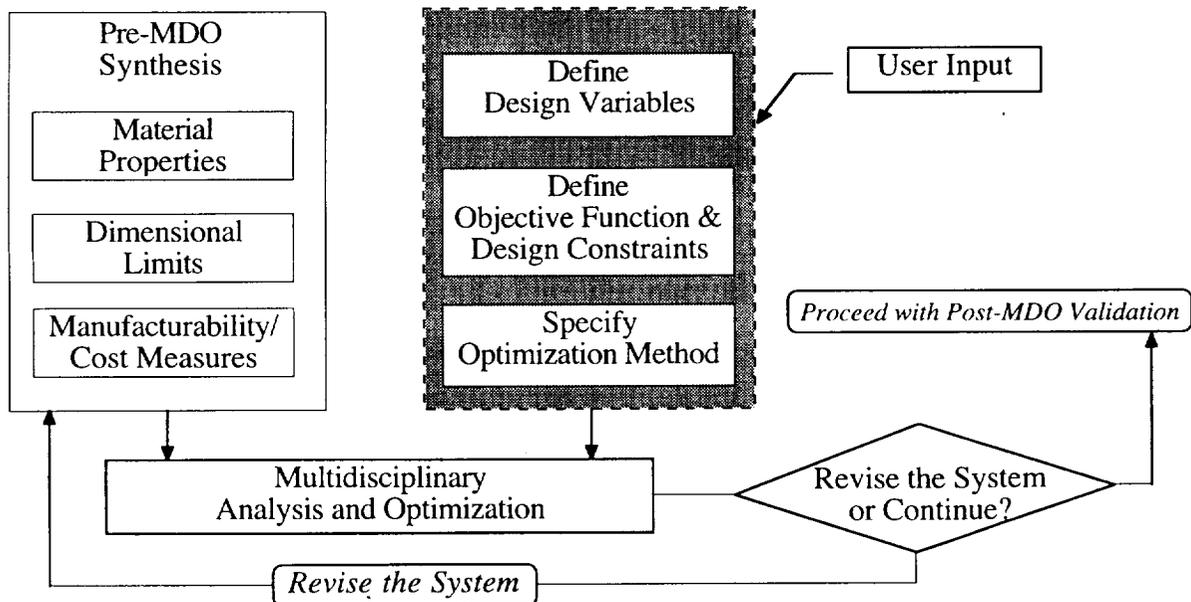


Figure 8. Design optimization procedure (MDO Analysis)

Table 2. User input for items ❶ through ❸ in Fig. 7

-
- ❶ Airplane Category/Class Identification (FAR part 1)
- a. normal, utility, acrobatic category airplanes
 - cruise speed: (a) low; (b) moderate; (c) high
 - engine type: (a) reciprocating; (b) turbo prop; (c) jet
 - number of engines: (a) 1; (b) 2; (c) 3; (d) 4
 - b. transport category airplanes
 - b.1 commuter class (11 < no. of passengers < 40)
 - cruise speed: (a) low; (b) moderate; (c) high
 - engine type: (a) reciprocating; (b) turbo prop; (c) jet
 - number of engines: (a) 1; (b) 2; (c) 3; (d) 4
 - b.2 large transport (no. of passengers > 40)
 - cruise speed: (a) moderate; (b) high
 - engine type: (a) turbo prop; (b) jet
 - number of engines: (a) 2; (b) 3; (c) 4
 - b.3 civil/military cargo
 - cruise speed: (a) moderate; (b) high
 - engine type: (a) turbo prop; (b) jet
 - number of engines: (a) 2; (b) 3; (c) 4
- ❷ System Definition (includes a computational model such as an FE mesh)
- a. wing box
 - a.1 to a.4 single, double, triple, or quad cell
 - a.5 combination (specify the number of cells in the inboard and outboard sections)
 - b. fuselage
 - b.1 to b.3 fore-section, mid / wing-section, aft-section
 - c. horizontal tail box
 - c.1 to c.3 single, double, or triple cell
 - d. vertical tail box
 - d.1 to d.3 single, double, or triple cell
- ❸ Features Identification (assuming wing box was chosen in ❷)
- Wing:
- a. straight, swept forward, or swept back [select one]
 - b. leading-edge break(s) [0, 1, or 2]
 - c. trailing-edge break(s) [0, 1, or 2]
 - d. chord taper [Y or N]
 - e. thickness taper [Y or N]
 - f. dihedral [None, Up, Down]
 - g. geometric twist [None, Small, Moderate, Large]
 - h. aerodynamic twist [None (1 airfoil), 2 airfoils, 3 airfoils]
 - i. control surfaces [Y or N]
 - flap(s) [0, 1, 2, or 3]
 - aileron [Inboard, Outboard, Both]
 - slat(s) [0, 1, 2, or 3]
 - spoiler(s) [0, 1, 2, or 3]
 - j. mechanical components [Y or N]
 - k. fuel tank(s) [Y or N]
 - if Y, integral or bladder [select one]
 - l. landing gear attachment(s) [Y or N]
 - m. engine attachment(s) [0, 1, or 2]

Table 2. User input for items ④ through ⑥ in Fig. 7 (Continued)

④ **Structural Anatomy Identification**

For example, in the case of a single-cell wing box the following information would have to be provided

• **Single-Cell Wing Box**

Upper skin:

- a. one piece (no assembly required) or multiple panels (assembly required)
- b. monolithic or sandwich
- c. stiffened or unstiffened
if stiffened, then
 - c-1. are all stringers continuous
 - c-2. are all stringers parallel to each other
 - c-3. do stringers have identical cross-sectional shape (as attached to skin)
 - c-4. do stringers have identical cross-sectional size
 - c-5. are all stringers uniform along their lengths
 - c-6. define material type and form, shape, and top 3 manufacturing processes for each stringer
 - c-7. how are stringers attached to skin (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!))
- d. chord wise curvature (low: $t/c < 5\%$, moderate: $5\% < t/c < 10\%$, high: $t/c > 10\%$; where t/c is the thickness-to-chord ratio of the wing)
- e. thickness variation (in chord wise direction, in spanwise direction, both, none)
- f. cutouts (specify shape and number)
- g. material type and form (e.g., aluminum alloy 7075-T6, plate)
- h. top 3 manufacturing processes (e.g., machining, heat treatment, age creep forming)

Lower skin:

(same questions as for the upper skin, but possibly with different answers)

Fore spar:

- a. one piece (integrated web and cap) or built-up cross section
if one piece, identify material type and form plus top 3 manufacturing processes
if built-up (web-cap assembly required), then
 - a-1. is web stiffened
if yes, stiffener only on one side (single) or on both sides (double)
 - a-2. what are web material type and form plus top 3 manufacturing processes
 - a-3. what are upper cap material type and form plus top 3 manufacturing processes
 - a-4. how is upper cap attached to the web (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!))
 - a-5. what are lower cap material type and form plus top 3 manufacturing processes
 - a-6. how is lower cap attached to the web (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!))
- b. single section (no spliced joints) or multiple sections (lap splice or splice plate) along its length
- c. is web flat
- d. is web thickness uniform
- e. is upper cap uniform
- f. is lower cap uniform
- g. is assembly required (If spar is one piece, the answer is no. This question does not apply to web-cap assembly.)
- h. how is the spar attached to the skin (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!)).

Table 2. User input for items ② through ④ in Fig. 7 (Continued)

Aft spar:

(same questions as for the fore spar, but possibly with different answers)

Ribs:

- a. number of ribs
- b. identical or different
if identical, the following data set should be entered only one time. if different, the following data set should be provided for each rib. However, the user would have the option of copying the same set of data for multiple ribs. This situation arises when a group of ribs are identical. Notice that identical means every single parameter remains the same.
- c. rib parallel to fuselage centerline or perpendicular to a designated spar
if perpendicular to a designated spar, identify the spar
- d. one piece or built-up cross section
if one piece, identify material type and form plus top 3 manufacturing processes
if built-up (web-cap assembly required), then
 - d-1. is web stiffened
if yes, stiffener only on one side (single) or on both sides (double)
 - d-2. what are web material type and form plus top 3 manufacturing processes
 - d-3. upper cap material type and form plus top 3 manufacturing processes
 - d-4. how is upper cap attached to the web (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!))
 - d-5. lower cap material type and form plus top 3 manufacturing processes
 - d-6. how is lower cap attached to the web (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!))
- e. is web flat
- f. is web solid or with lightening holes
- g. is web thickness uniform
- h. is upper cap uniform
- i. is lower cap uniform
- j. is assembly required (if rib is one piece, the answer is no. This question does not apply to web-cap assembly.)
- k. depending on the answer to question b, repeat d through k for the remaining ribs
- l. ribs attached to stringers or skin or both.
- m. how are the ribs attached to the part specified in l (mechanically fastened, adhesively bonded, fastened and bonded, or cocured (for composites only!)).

It must be pointed that items 2 through 4 in Fig. 7 and Table 2 can be extracted from a parametric CAD model of the system being evaluated or optimized. Such a system is currently being developed using Unigraphics™ CAD tool. Also for engineering analysis of the system a computational model is required. For example, if finite element analysis is to be performed, then a finite-element mesh of the system would need to be developed as part of system definition.

A prototype model of TASPI for beam and frame type structures typical of spars, ribs, and floor beams has been developed. The description of this prototype along with an example problem are provided in part 2 of this report.

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